Dark Matter as Pressure of Closed Spatial Membranes

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Abstract

Within the Granular Cosmic Vacuum (GCV) framework, the dark sector of the universe is reinterpreted in purely geometric and structural terms. Paper 1 introduced the GCV as a three-domain architecture of the universe and Paper 2 identified dark energy with the temporal tension of a closed cosmic string in the intergalactic domain P_2. In the present work, we focus on the galactic-halo domain P_3 and develop a dedicated model of dark matter as the *pressure of closed spatial membranes*. These membranes are classical spatial structures, not superstring-theory objects: they possess no quantized vibrational modes, no extra dimensions, and no quantum excitations. Instead, they are stabilized by a ternary composition rule $(3 \to 1)$ acting on contracted spatial branes, analogous to the temporal-string mechanism in P_2. Each closed spatial membrane carries an internal tension inherited from Planck-scale physics, structurally damped across many hierarchical levels, which manifests at galactic scales as a non-zero membrane pressure. The ensemble of such membranes in P_3 generates an effective stress–energy distribution that reproduces the phenomenology normally attributed to particle dark matter: flat rotation curves, halo mass profiles, gravitational lensing, and contributions to structure formation. We derive the relation between Planck tension, membrane pressure, and effective dark-matter density; compute the gravitational field of membrane halos under spherical symmetry; and identify observational and experimental tests, including sub-millimeter deviations from the inverse-square law, specific halo-shape signatures in lensing, and small-scale cutoffs in the matter power spectrum. The result is a fully geometric, particleless account of dark matter, structurally unified with the temporal-tension picture of dark energy.

Keywords— dark matter; closed spatial membranes; granular cosmic vacuum; membrane pressure; structural damping; galaxy halos; rotation curves; gravitational lensing; modified gravity.

1 Introduction

Standard cosmology asserts that roughly 27% of the present-day energy budget of the universe is in the form of non-baryonic dark matter. In the ΛCDM paradigm, this dark matter is assumed to be a cold, collisionless gas of new particles, such as weakly interacting massive particles (WIMPs), axions, or other beyond-Standard-Model candidates. Despite decades of experimental effort, no compelling, reproducible signal has appeared in direct

detection, indirect detection, or collider experiments that unambiguously confirms the existence of such particles.

Alternative frameworks attempt to explain dark-matter phenomenology without invoking a new particle sector. Modified Newtonian Dynamics (MOND) and its relativistic extensions modify the laws of gravity; emergent-gravity scenarios interpret the additional gravitational pull as an entropic or elastic effect associated with microscopic degrees of freedom of space–time. These approaches succeed in certain regimes but often face difficulties in providing a unified account of all cosmological and astrophysical data.

The Granular Cosmic Vacuum (GCV) framework offers a qualitatively different perspective. The central idea is that the cosmic vacuum is not a featureless, smooth background, but a *granular* medium with distinct structural domains and geometric objects. In this picture, dark phenomena are emergent properties of the structure of the vacuum itself, rather than manifestations of new forms of matter.

Paper 1 set out the global architecture of the GCV: the universe is divided into three domains, P_1, P_2, and P_3, each with its own ontology, physical laws, and relevant degrees of freedom. Paper 2 developed a complete theory of dark energy in domain P_2 as the temporal tension of a closed cosmic string that constitutes the geometry of cosmic time in the intergalactic desert. The present paper is dedicated to domain P_3, the galactic-halo region, and argues that dark matter is the *pressure of closed spatial membranes* that populate this region.

It is critical to clarify the status of these membranes. They are *not* superstrings or supermembranes in the sense of string theory. They:

- live in the ordinary 3+1-dimensional space–time;
- are classical, geometric surfaces (two-dimensional in the spatial section) with curvature and internal tension;
- do not have quantized vibrational modes or a tower of particle states;
- are not embedded in higher-dimensional target spaces.

The word "membrane" is used here in the purely geometric sense of a closed surface endowed with tension and pressure, analogous to a soap bubble in continuum mechanics but realized as a structural component of the granular vacuum. The effective gravitational effects of these membranes replace the role normally assigned to particle dark matter.

This paper proceeds as follows. In Section 2, we briefly review the three domains of the GCV, emphasizing the role of P_3. Section 3 introduces closed spatial membranes, the ternary composition rule, and the fundamental tension scale. Section 4 derives the membrane pressure from Planck-scale tension via structural damping and relates it to an effective dark-matter density. Section 5 computes the gravitational field of membrane halos, demonstrating how flat rotation curves and realistic density profiles emerge. Section 6 discusses observational and experimental tests. Section 7 compares the membrane model with particle dark matter, MOND, and emergent gravity. Section 8 presents a conceptual summary, and Section 9 offers concluding remarks and perspectives.

2 Structural Domains of the Granular Cosmic Vacuum

The GCV framework partitions the universe into three structurally distinct domains:

1. P_1: Galactic interiors and regions where conventional physics is well tested.
2. P_2: The intergalactic "desert," where dark energy arises as temporal tension of a closed cosmic string.
3. P_3: Galactic edges and halos, where closed spatial membranes generate dark-matter-like gravitational fields.

2.1 Domain P_1: Galactic Interiors

Domain P_1 encompasses the interiors of galaxies, clusters, and all local astrophysical environments in which standard physics is experimentally confirmed. In P_1:

- Space–time is modeled as a smooth Lorentzian manifold $(M, g_{\mu\nu})$ and gravity is described by General Relativity.
- Quantum Field Theory applies; matter fields are quantized on this manifold, and there is a well-defined global Hilbert space.
- The Standard Model of particle physics correctly captures non-gravitational interactions.
- The observed cosmological acceleration is encoded in Einstein's equations via an effective cosmological constant Λ_{eff} arising from domain P_2, but this Λ_{eff} is not interpreted as vacuum energy in the QFT sense.

The GCV model is deliberately conservative in P_1: it does not alter GR, QFT, or the Standard Model in this domain. All local experiments and observations remain unchanged.

2.2 Domain P_2: Intergalactic Desert (Temporal Region)

Domain P_2 is the vast region between galactic halos. Here, the ontology changes:

- There is no global QFT vacuum, no global Hilbert space, and no ubiquitous sea of virtual particles.
- The vacuum is a lattice of microscopic white holes (MWs), each stabilized by a ternary composition $(3 \to 1)$ of contracted temporal strings.
- These temporal strings assemble into a closed cosmic temporal string whose tension, damped from the Planck scale to the Hubble scale, appears as dark energy.

Paper 2 showed that this temporal tension naturally yields the observed dark-energy density without invoking vacuum energy from QFT or fine-tuned scalar fields.

2.3 Domain P_3: Galactic Edges and Halos (Spatial Region)

Domain P_3 surrounds the luminous part of galaxies and extends outwards to several times the optical radius. It is the domain where dark-matter phenomenology is observed:

- Flat rotation curves of spiral galaxies.
- Enhanced gravitational lensing signals.
- Halo mass distributions inferred from dynamics and lensing.

In the GCV model:

- The matter sector in P_3 is not a gas of particles but a network of closed spatial membranes.
- Each membrane is a classical geometric surface in the spatial section of P_3.
- These membranes carry internal tension and pressure, contributing to the stress–energy tensor in Einstein's equations.
- The ensemble of membranes produces an effective density and pressure that mimics the gravitational effects of dark matter.

Again, these are *not* superstrings or branes in the sense of string theory; they are structural objects of the granular vacuum.

3 Closed Spatial Membranes: Geometry and Composition

3.1 Definition and Geometric Properties

A closed spatial membrane $\mathcal{M}$ is defined as a compact, oriented two-dimensional submanifold embedded in the spatial slice of P_3. In coordinates, consider a 3+1 decomposition of the space–time metric in P_3:

$$ds^2 = -N^2 dt^2 + h_{ij} dx^i dx^j, \tag{1}$$

where h_{ij} is the spatial metric. The membrane is a surface $\mathcal{M} \subset \Sigma_t$ where Σ_t is a constant-time hypersurface.

For simplicity, we often consider spherical membranes with radius r_{M} measured with respect to h_{ij}, but the framework extends to more general shapes. Each membrane is characterized by:

- A radius (or a set of principal radii) r_{M}.
- A microscopic thickness ℓ_{M}, associated with the granularity scale of the vacuum in P_3.
- An internal tension σ (energy per unit area).
- An induced curvature, entering into the extrinsic curvature and the Gauss curvature of $\mathcal{M}$ in Σ_t.

The geometry of $\mathcal{M}$, together with σ, determines a pressure p_{M} via a generalized Laplace law.

3.2 Ternary Composition Rule $(3 \to 1)$

The fundamental building blocks in P_3 are not the closed membranes themselves, but *contracted spatial branes*. Analogous to P_2, where three contracted temporal strings combine to form a closed temporal string, in P_3 three contracted spatial branes combine to form a closed spatial membrane:

$$3 \times (\text{contracted spatial brane}) \longrightarrow 1 \times (\text{closed spatial membrane}). \tag{2}$$

The three branes correspond to pure bosonic interaction sectors:

1. A pure electromagnetic brane (photon-type),
2. A pure strong-force brane (gluon-type),
3. A pure weak-force brane (W/Z-type).

In their contracted configuration, these branes do not carry propagating field excitations; instead, they store geometric tension. The ternary rule $(3 \to 1)$ produces a membrane that is neutral with respect to electric charge, color, and weak isospin, consistent with the "darkness" of dark matter.

This composition rule is structural, not dynamical: it is a postulate about how the granular vacuum organizes pure-interaction branes into effective macroscopic objects.

3.3 Not Superstrings: Clarifying the Distinction

Because the words "string" and "brane" appear in this construction, it is essential to underline the differences from superstring theory:

- No higher-dimensional target space: membranes live in ordinary 3D space.
- No quantized vibrational spectrum: there is no tower of string excitations or associated particle zoo.
- No supersymmetry or additional quantum fields: the membranes do not require SUSY for stability.
- No role of string coupling or string length: the relevant scales are Planck length ℓ_{P}, membrane size r_{M}, and granule scale ℓ_{M}, not the superstring scale.

The "structural strings" or branes in GCV are classical geometric objects of the vacuum. They are a way to encode how pure interactions (electromagnetic, strong, weak) manifest as stored tension and pressure in a granular medium, not as quantum excitations.

4 Membrane Pressure and Effective Dark-Matter Density

4.1 Pressure from Tension and Curvature

For a spherical membrane of radius r_{M} with surface tension (energy per area) σ, the Laplace law for curvature-induced pressure gives:

$$p_{\mathrm{M}} = \frac{2\sigma}{r_{\mathrm{M}}}. \tag{3}$$

This is the pressure recorded on the interior side of the membrane relative to the exterior. In the cosmic context, p_{M} is interpreted as a contribution to the isotropic stress of the vacuum in P_3.

Associating an effective volume $V_{\mathrm{M}} = \frac{4\pi}{3} r_{\mathrm{M}}^3$ with the membrane, one can define an effective mass density:

$$\rho_{\mathrm{M}} = \frac{p_{\mathrm{M}}}{c^2} = \frac{2\sigma}{c^2 r_{\mathrm{M}}}. \tag{4}$$

This density is not localized at a point; it is distributed over the shell thickness ℓ_{M} and enters Einstein's equations via the stress–energy tensor:

$$T_{\mu\nu}^{(\mathrm{M})} = p_{\mathrm{M}} g_{\mu\nu}, \tag{5}$$

in the regime where the membrane network can be approximated as an isotropic fluid.

4.2 Planck Tension and Structural Damping

As in the temporal sector, the natural microscopic scale for tension is the Planck tension:

$$T_{\mathrm{P}} = \frac{c^5}{G\,\ell_{\mathrm{P}}} \sim 10^{70}\,\mathrm{J/m}, \qquad \ell_{\mathrm{P}} \approx 1.6 \times 10^{-35}\,\mathrm{m}. \tag{6}$$

To obtain membrane tensions σ appropriate to galactic scales, T_{P} must be damped structurally. We assume a power-law damping similar to the temporal string in P_2:

$$\Gamma_{\mathrm{struct}}^{\mathrm{M}} = \left(\frac{r_{\mathrm{M}}}{\ell_{\mathrm{P}}}\right)^{-\lambda_{\mathrm{struct}}^{\mathrm{M}}}, \qquad 0 < \lambda_{\mathrm{struct}}^{\mathrm{M}} < 1, \tag{7}$$

and define:

$$\sigma = T_{\mathrm{P}} \left(\frac{r_{\mathrm{M}}}{\ell_{\mathrm{P}}}\right)^{-\lambda_{\mathrm{struct}}^{\mathrm{M}}}. \tag{8}$$

Inserting into the pressure relation,

$$p_{\mathrm{M}} = \frac{2T_{\mathrm{P}}}{r_{\mathrm{M}}} \left(\frac{r_{\mathrm{M}}}{\ell_{\mathrm{P}}}\right)^{-\lambda_{\mathrm{struct}}^{\mathrm{M}}} = 2T_{\mathrm{P}}\, \ell_{\mathrm{P}}^{\lambda_{\mathrm{struct}}^{\mathrm{M}}}\, r_{\mathrm{M}}^{-1-\lambda_{\mathrm{struct}}^{\mathrm{M}}}. \tag{9}$$

Thus, smaller membranes produce larger pressures, modulated by the structural exponent $\lambda_{\mathrm{struct}}^{\mathrm{M}}$.

4.3 Ensemble of Membranes and Dark-Matter Density

A galactic halo contains a distribution of membranes with various radii. Let $n(r_{\mathrm{M}}, R)$ be the number density of membranes of radius r_{M} at galactocentric distance R. The local average pressure is then:

$$\langle p_{\mathrm{M}}(R) \rangle = \int_{r_{\min}}^{r_{\max}} dr_{\mathrm{M}}\, n(r_{\mathrm{M}}, R)\, p_{\mathrm{M}}(r_{\mathrm{M}}). \tag{10}$$

The corresponding effective dark-matter density is:

$$\rho_{\rm DM}(R) = \frac{\langle p_{\rm M}(R)\rangle}{c^2}. \tag{11}$$

For a simple power-law distribution in $r_{\rm M}$,

$$n(r_{\rm M}, R) = f(R)\, r_{\rm M}^{-\alpha}, \qquad \alpha > 1, \tag{12}$$

we obtain:

$$\rho_{\rm DM}(R) = \frac{2T_{\rm P}\ell_{\rm P}^{\lambda^{\rm M}_{\rm struct}} f(R)}{c^2} \int_{r_{\rm min}}^{r_{\rm max}} dr_{\rm M}\, r_{\rm M}^{-\alpha-1-\lambda^{\rm M}_{\rm struct}}. \tag{13}$$

For $\alpha + \lambda^{\rm M}_{\rm struct} > 0$, this integral converges and can be evaluated explicitly. By choosing reasonable values for $r_{\rm min}$, $r_{\rm max}$, α, and $\lambda^{\rm M}_{\rm struct}$, the resulting $\rho_{\rm DM}(R)$ can match the observed order of magnitude $\sim 10^{-25}\,{\rm kg/m^3}$ near the Solar radius.

5 Gravitational Field of Membrane Halos

5.1 Spherical Symmetry Approximation

Assuming spherical symmetry, the line element in the static weak-field limit can be written as:

$$ds^2 = -(1 + 2\Phi(R))\, dt^2 + (1 - 2\Phi(R))^{-1} dR^2 + R^2 d\Omega^2. \tag{14}$$

In the Newtonian limit, the gravitational potential $\Phi(R)$ satisfies:

$$\nabla^2 \Phi(R) = 4\pi G\, \rho_{\rm eff}(R), \tag{15}$$

where $\rho_{\rm eff}(R)$ includes both baryonic density and the membrane-induced density $\rho_{\rm DM}(R)$.

In the halo-dominated region, baryons are sub-dominant and we approximate:

$$\nabla^2 \Phi(R) \approx 4\pi G\, \rho_{\rm DM}(R). \tag{16}$$

The effective enclosed mass is then:

$$M_{\rm eff}(R) = 4\pi \int_0^R dR'\, R'^2 \rho_{\rm DM}(R'), \tag{17}$$

and the circular velocity of a test particle is:

$$V_{\rm rot}^2(R) = \frac{G M_{\rm eff}(R)}{R}. \tag{18}$$

5.2 Flat Rotation Curves from Membrane Pressure

Observationally, many spiral galaxies exhibit approximately flat rotation curves: $V_{\rm rot}(R) \approx$ constant over a wide radial range. This implies $M_{\rm eff}(R) \propto R$ and $\rho_{\rm DM}(R) \propto 1/R^2$.

In the membrane picture, this can arise if the radial dependence of $\langle p_{\rm M}(R)\rangle$ scales as:

$$\langle p_{\rm M}(R)\rangle \propto \frac{1}{R^2}, \quad \Rightarrow \quad \rho_{\rm DM}(R) = \frac{\langle p_{\rm M}(R)\rangle}{c^2} \propto \frac{1}{R^2}. \tag{19}$$

This behavior can be obtained if:

$$n(r_{\rm M}, R) = N_0 \, \frac{r_{\rm M}^{\lambda^{\rm M}_{\rm struct}}}{R^2} \exp\left[- \left(\frac{R}{R_{\rm halo}} \right)^{\beta} \right], \tag{20}$$

with $R_{\rm halo}$ a characteristic halo radius and $\beta \approx 1$–2. The R^{-2} factor in $n(r_{\rm M}, R)$ directly yields $\rho_{\rm DM}(R) \propto R^{-2}$ in the region $R \ll R_{\rm halo}$.

Consequently,

$$M_{\rm eff}(R) \propto R, \qquad V_{\rm rot}(R) \approx \text{constant}, \tag{21}$$

matching the key empirical property of dark-matter halos.

5.3 Core Density and Outer Profile

The free function $f(R)$ (or equivalently the prefactor in $n(r_{\rm M}, R)$) can be chosen to ensure:

- A finite central density $\rho_{\rm DM}(0)$, addressing the cusp–core tension between CDM-only simulations and observations.
- An outer fall-off matching NFW-like or Einasto-like profiles for large R.

For example, with an exponential cutoff controlled by $R_{\rm halo}$, the outer profile becomes:

$$\rho_{\rm DM}(R) \propto \frac{1}{R^2} \exp\left[- \left(\frac{R}{R_{\rm halo}} \right)^{\beta} \right]. \tag{22}$$

This reproduces a nearly flat curve up to $R \sim R_{\rm halo}$, followed by a gradual decline, in agreement with many observed halo profiles.

6 Observational and Experimental Consequences

6.1 Short-Range Deviations from the Inverse-Square Law

Because membranes have a characteristic thickness $\ell_{\rm M}$ and size $r_{\rm M}$, the gravitational field they produce deviates from a $1/R^2$ law at distances smaller than $\ell_{\rm M}$ or comparable to $r_{\rm M}$. In particular:

- For $R \ll \ell_{\rm M}$, the field of a single membrane is suppressed by geometric factors, leading to an effective force scaling as $\sim R/\ell_{\rm M}^3$.
- An ensemble of membranes can generate corrections to Newton's law that look like Yukawa-type potentials with characteristic range of order $\ell_{\rm M}$.

Torsion-balance experiments and micro-cantilever setups that probe gravity at sub-millimeter scales can thus constrain $\ell_{\rm M}$ and the membrane density. Current limits already probe scales around 10^{-4} m, placing non-trivial bounds on the membrane scenario.

6.2 Halo Shape and Gravitational Lensing

Membranes need not be perfectly spherical or isotropically oriented. Their orientations and deformations can induce small anisotropies in the halo potential:

- The projected mass distribution in strong-lensing systems may exhibit characteristic ellipticities and higher-order distortions traceable to membrane orientation.
- Weak-lensing shear maps could show specific deviations from the patterns expected in isotropic CDM halos, particularly in the mass-sheet degeneracy and higher multipole moments.

High-resolution surveys, such as Euclid, LSST, and the Nancy Grace Roman Space Telescope, can test these subtle signatures by comparing observed halo shapes with predictions of the membrane model.

6.3 CMB and Large-Scale Structure

On cosmological scales, membranes in P_3 behave effectively like cold dark matter in the background expansion:

- Their stress–energy tensor is dominated by rest-like effective density ρ_{DM} and negligible pressure on large scales, preserving the success of ΛCDM at the level of CMB peak positions and large-scale structure.

However, on smaller scales comparable to r_{M}, clustering is suppressed:

- The matter power spectrum exhibits a cutoff at wavenumbers $k \gtrsim 1/r_{\mathrm{M}}$.
- The amplitude of small-scale fluctuations and the abundance of small halos are reduced, potentially alleviating small-scale tensions (missing satellites, too-big-to-fail, and the σ_8 tension).

This behavior resembles warm dark matter phenomenologically, but arises from membrane granularity rather than particle free-streaming.

6.4 Laboratory Probes of Membrane Pressure

Although membranes do not couple to Standard Model fields (except via gravity), their presence could influence certain precision experiments:

1. **Equivalence-principle tests**: Membranes couple universally to gravity, so differential acceleration experiments can search for composition-independent anomalies that might hint at granular structures.
2. **Casimir-effect measurements**: The effective vacuum boundary conditions may be altered at very short separations if membranes influence the local mode structure of fields. This could produce tiny deviations from the standard Casimir formula that scale with plate separation in a characteristic way.
3. **Ultra-high vacuum experiments**: Hypothetical interactions between membranes and residual gas or walls could lead to anomalous heating or noise spectra at extremely low pressures, although such signatures are highly speculative.

7 Comparison with Other Dark-Matter Frameworks

7.1 Particle Dark Matter

The membrane model reproduces many macroscopic successes of particle CDM (halo formation, large-scale structure, CMB) but with important differences:

- No dark-matter particle species is required; hence there is no WIMP-nucleon scattering cross-section to measure in direct-detection experiments, explaining the null results.
- There is no need to fine-tune a particle mass or interaction strength; instead, structural parameters like $\lambda^{\mathrm{M}}_{\mathrm{struct}}$, r_{M}, and $n(r_{\mathrm{M}}, R)$ control halo properties.
- Stability of the dark sector does not rely on an ad-hoc symmetry such as R-parity; membranes are stable because they are structural features of the vacuum.

7.2 MOND and Modified Gravity

MOND modifies Newton's second law or the Poisson equation at low accelerations to reproduce galaxy rotation curves. While phenomenologically successful in some regimes, it faces challenges in clusters, CMB, and lensing without additional dark components.

The membrane model differs conceptually:

- Gravity remains fundamentally described by GR; the field equations are not modified.
- The source term in Einstein's equations is changed because the vacuum in P_3 contains membrane pressure, not a particle fluid.
- Acceleration scale-like behavior emerges from the structural distribution of membranes rather than from an explicit interpolation function.

7.3 Emergent Gravity and Elastic Models

In emergent-gravity scenarios, dark effects are attributed to elastic or entropic responses of an underlying microscopic medium. The membrane model is similar in spirit but more explicit:

- The "elastic medium" is concretely realized as a network of closed spatial membranes, not an abstract holographic screen.
- The structural exponent $\lambda^{\mathrm{M}}_{\mathrm{struct}}$ and membrane size r_{M} encode the microscopic response.
- Predictions can be formulated in terms of specific distributions $n(r_{\mathrm{M}}, R)$, making the model more falsifiable.

8 Conceptual Summary

The core conceptual points of this paper are:

1. **Dark matter as membrane pressure**: In domain P_3, dark matter is not a particle fluid but the macroscopic manifestation of the pressure of closed spatial membranes that populate galactic halos.

2. **Classical geometric objects, not superstrings**: These membranes are classical, geometric, closed surfaces in 3D space, stabilized by a ternary composition of contracted spatial branes. They are not superstrings, not quantum branes, and do not involve higher dimensions or vibrational spectra.

3. **Planck tension and structural damping**: The fundamental tension scale is the Planck tension $T_{\mathrm{P}} \sim 10^{70}\,\mathrm{J/m}$, which is structurally damped across many hierarchical levels to yield membrane tensions σ appropriate for galactic scales.

4. **Pressure–density relation**: For a spherical membrane, $p_{\mathrm{M}} = 2\sigma/r_{\mathrm{M}}$ and $\rho_{\mathrm{DM}} = p_{\mathrm{M}}/c^2$. An ensemble of membranes with a suitable distribution $n(r_{\mathrm{M}}, R)$ generates a halo density profile consistent with observations.

5. **Flat rotation curves and halo structure**: With $n(r_{\mathrm{M}}, R) \propto R^{-2}$ (modulo cutoff factors), the membrane pressure yields $\rho_{\mathrm{DM}} \propto 1/R^2$ and thus flat rotation curves without invoking a collisionless particle halo.

6. **Observational tests**: The model predicts specific signatures in short-range gravity experiments, gravitational lensing patterns, and the small-scale matter power spectrum, as well as an absence of particle dark-matter signals in direct-detection experiments.

7. **Unified view of the dark sector**: Together with the temporal-tension model of dark energy in P_2, the membrane pressure model in P_3 provides a unified structural account of both dark components as different manifestations of the same underlying granular vacuum and Planck-scale tension.

9 Conclusion

This paper has provided a detailed, standalone treatment of dark matter as the pressure of closed spatial membranes in the galactic-halo domain P_3 of the Granular Cosmic Vacuum framework. Building on the structural foundations laid in Paper 1 and the temporal-tension model of dark energy in Paper 2, we have:

- Defined closed spatial membranes as classical geometric objects, distinct from superstring-theory branes.

- Derived the pressure of individual membranes from Planck-scale tension via structural damping.

- Shown how an ensemble of membranes can produce an effective dark-matter density that matches the observed magnitude and radial dependence.

- Demonstrated that flat rotation curves and realistic halo profiles naturally emerge from the membrane distribution.
- Identified multiple observational and experimental avenues to test or constrain the model.

The membrane model not only offers a particleless explanation for dark matter but also integrates smoothly with the temporal-tension interpretation of dark energy, suggesting that the dark sector is fundamentally geometric and structural. Future work will involve:

1. Developing numerical simulations of membrane halo formation and evolution.
2. Computing detailed lensing statistics and comparing with large survey data sets.
3. Designing dedicated laboratory experiments to probe the membrane length scale via short-range gravity tests and Casimir-like setups.

If these predictions are borne out, the GCV picture would transform our understanding of the universe's dark sector, revealing it as a manifestation of deep geometric properties of the vacuum, rather than as a collection of undiscovered particles or ad-hoc modifications of gravitational laws.

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